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SUMMARY REPORT 1

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FUTURE DEVELOPMENTS OF OPERATIONS RESEARCH

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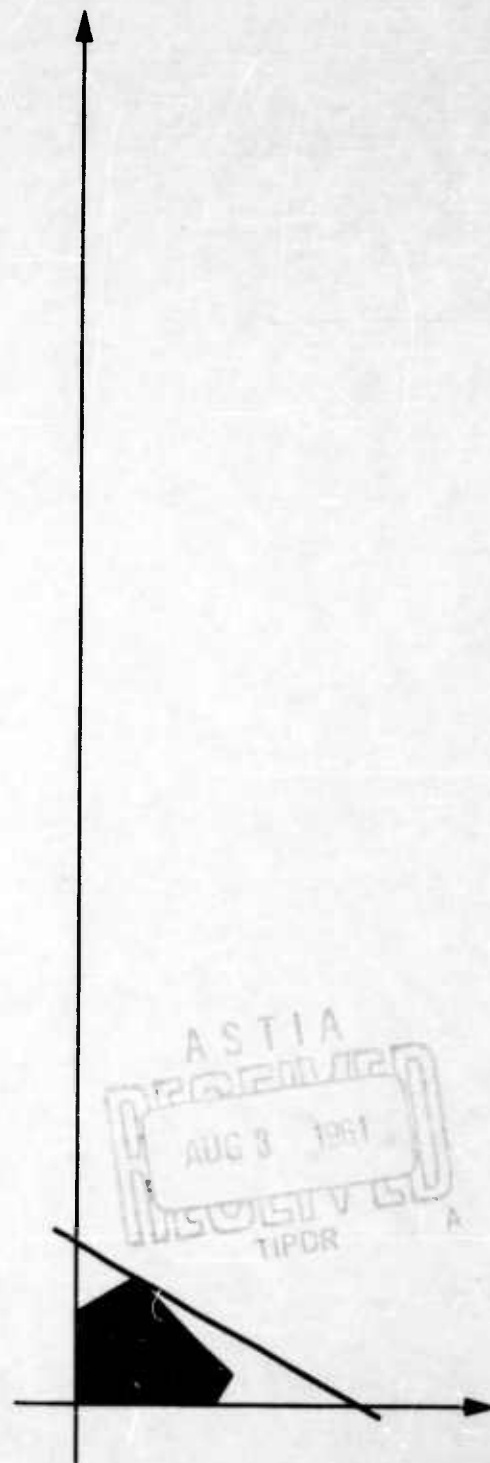
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FUTURE DEVELOPMENT OF OPERATIONS RESEARCH

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March 3, 1961

Summary Report 1

SUMMARY

This paper was read before the Thirteenth Annual Industrial Engineering Institute*(February 3-4, 1961), University of California, Berkeley and is expected to be published as part of the proceedings of the conference. Topics covered include a general discussion of the relation between (1) studies dealing with decision theory and shifting emphasis in engineering service, (2) the general research program of a new center of operations research in the College of Engineering at Berkeley, (3) the need for a sustained base of research in the operations research to take advantage of several successful research breakthroughs. This was followed by a discussion of two particular research developments: (4) Integrated Planning-Execution Theory, and (5) Decentralized Decision-Making, using a Decomposition Principle Approach.

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As a result of the growth of industrial and government complexes, and the wartime progress in information handling, computation, and analysis, the post-war period has been marked by advances in the use of the scientific method for the planning and control of operational systems. This effort has been characterized by an increasing flow of information through operational and statistical reporting systems, and by the increasing use of planning tools (such as balanced programs and budgets). Although many of these techniques are not especially sophisticated, they must be appreciated as part of a movement toward simulation of large scale systems in order to better evaluate alternative decision possibilities and to effect better control of operations.

Out of this effort is emerging a new science, concerned with the problems of rapidly selecting optimal courses of action from many alternatives. This development, in conjunction with the mechanization of many simple, human, control tasks, foreshadows for the future the automation of many higher level, mental processes. In the not-too-distant future, machines will undertake many complex control tasks.

The broad group of studies dealing with decision theory and its applications, popularly referred to as "Operations Research," includes investigations which have led to the development and generalization of new mathematical disciplines,

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such as linear programming, game theory, dynamic programming, and extensions to older disciplines, such as mathematical statistics. The products of this research have found successful application to decision problems of man-machine systems involving production, allocation, and distribution under stochastic, deterministic, and competitive conditions. This, in turn, has opened to consideration a host of new questions, calling for an expanded research program and additional trained personnel capable of doing research and of selecting and applying the available techniques to appropriate subject matter fields.

In contrast, the central function of engineering in society is the creation of predictable systems of facilities and processes for the performance of required tasks within specified time limits and budgets. Some essential aspects of this creative process are (1) planning and design (involving conception, analysis, and prediction of performance and cost); (2) direction and control of fabrication, construction, and processing (as governed by time and cost constraints); and (3) in all these aspects, the exercise of skill and judgment in the synthesis of requirements and the compromise of conflicts. While engineers, as individuals, may at any one time perform many specialized functions over the range of engineering effort, this philosophy of feasible design permeates and gives drive and meaning both to engineering education and to practice in all the separate specialties which comprise the spectrum of engineering activity.

Contrary to the focus of an earlier day upon design of isolated elements and processes, recent socio-economic and technological developments have created an urgent need for analysis of complete system and for design of increasingly complex systems of facilities and processes. Thus, increasing emphasis is devolving upon research as an indispensable component of engineering science and academic procedure.

In this connection, modifications of engineering education are already taking place at the University of California. Some of these changes are (1) strengthening of the scientific base in engineering education and in curtailment of over-specialization in undergraduate curricula (together with increased emphasis on socio-humanistic studies); (2) growing recognition of graduate study as an all but indispensable preparation for engineering practice in its most professional and creative aspects; (3) incorporation of high-level professional programs with design orientation, and programs emphasizing research as a preparation for teaching and developmental work.

It is with these developments in mind that the Operations Research Center of the Institute of Engineering Research was set up last September at the University of California at Berkeley. Its purpose is to engage in research into methods for the analysis, effective design, and control of man-machine systems.

The activities of the Center are designed to contribute to the evolution of this field of Engineering Science. The Center will complement existing formal academic courses by providing a much needed "laboratory-type environment" where decision problems can be subjected to mathematical and experimental analysis, and where, moreover, students and faculty alike can obtain "field" experience.

The General Nature of the Research

In the years preceding World War II, mathematics had received powerful stimulation from problems arising in the pure sciences (notably in physics and chemistry). By contrast, the post-war years have seen the emergence of a mathematics rooted largely in the applied sciences.

Concurrently, far-reaching advances in computer engineering have taken place and, as a consequence, mathematics is now playing a major role, not only in the sciences themselves, but also in application to the complex management and design problems of government and industry. Thus, hand in hand with great advances in the engineering arts have come mathematical procedures specifically designed to exploit the potentialities of the enormous computational power these arts have made available.

The problem of effective control of a system is closely related to the question of what decisions to make in order to improve its over-all operation. If a decision is characterized as a choice of actions to be taken, then the problem is one of picking (rather than creating) some course of action out of the many existing alternatives in such a way as to maximize some objective function which measures performance of the system as a whole. Once a problem is formulated as a mathematical model, a mathematical problem arises -- that of finding an analytic or numerical solution which satisfies the conditions of the model and maximizes the objective function.

One important class of decision processes is program planning. Industrial production, the directed flow of resources in an economy, the exertion of defense effort -- all are complexes of interrelated activities which require

program planning. The term 'programming', as used here, means scheduling the selection, timing and extent of activities to be performed so that a system may move from some fixed status toward a desired objective. When interrelations between the levels of various activities throughout the program are abstracted in mathematical terms, the resulting representation is referred to as a mathematical programming model. If, in addition, the mathematical description satisfies assumptions of proportionality, additivity and nonnegativity, it is called a linear-programming model.

With all the Accomplishments to Date, There is a Need More than Ever for a Sustained Program of Basic and Applied Research

From 1947 on, rapid progress in the use of mathematical decision models can be attributed largely to the fortuitous development of techniques -- such as the simplex method for solving linear programs -- independently of actual applications and well in advance of them. Yet it is doubtful if any of those who were ultimately to benefit by these applications could have foreseen their importance with enough clarity to support the basic research required to bring them about. Rather, it has been the other way around -- the tool inspired the application.

A survey of the present situation shows that such industries as those processing petroleum, food, and lumber products would now be willing to undertake full mathematical scheduling of their systems, if research could produce a practical method for solution of sufficiently large programs. Yet it is doubtful if any company can at present undertake to support the basic research necessary to bring this about.

To date, research in the mathematical programming field has received the major part of its support from the military and, therefore, has frequently been oriented toward military ends. Benefits to the general economy, through great, have been in the nature of by-products.

The growth of applications has been so rapid that development of supporting mathematical theory has fallen behind and is becoming a bottleneck to further progress.

If the trend toward increasing use of mathematics in planning and control is to continue, there is an immediate need for a greatly increased base of

direct support for fundamental research into mathematics bearing on the processes of operational decision.

In order to make concrete the discussion of future developments in Operations Research, and to elaborate further upon the needs for sustained programs of research, I have selected two topics in the Theory of Planning and Control that may be of special interest to engineers. The first of these is:

I. Integrated Planning-Execution Theory

We believe that it is important to develop theory and techniques for integrating, in a precise way, the planning and execution functions of large scale systems. At present, those echelons responsible for day-to-day control, as well as those engaged in long-range planning within a system, usually have access to a plethora of information which, more or less, mirrors the real world. Broadly speaking, this information is combined with simplifying plans to form a base for developing operational decisions. The resulting programs are generally used to effect over-all policy with, however, no precise means of translation into detailed particular decisions. Conversely, there is usually a corresponding lack of precise means for re-evaluating a plan in the light of new developments. In spite of this, it generally is believed that great economies can result from the use of scientific planning methods, but the gap between the paper plan and the day-to-day actions which it purports to control is so great that this has never been substantiated. It is hoped that the research contemplated for integrated planning-execution models may, in time, provide industry with a way to make analytical planning both effective and practical.

The general approach which we have been considering at the Operations Research Center will be to study some system (such as a supply, a communication, or an air traffic system) with the object of providing a "brain" to control it. Like an organic brain, it will need a precise way to couple its activities to those of the system; moreover, this is to be done in such a way that long range objectives and day-to-day decisions are coordinated. This interconnection will be made at first, not with the real world (which could hardly afford us the luxury of such an experiment), but with a detailed "descriptive model" of the system's operation which previously will have been developed.

The first step to the approach just sketched, consists in developing a mathematical (or logical) description of the detailed operating characteristics of typical systems encountered in applied fields.

Since a completely detailed decision model for the system as a whole could be too complicated, the second step will be to develop a solvable mathematical model for determining some optimal policy for the system as a whole, based upon simplified assumptions and suppression of detail. For example, based on certain simplifying assumptions with regard to the uncertainties in the flow patterns through a communication or traffic system, a mathematical model might be developed which (when solved) would yield an optimal routing decision which could take account of both long- and short-term considerations.

The third step will be the development of an interconnecting set of sub-models which will yield precise procedures for translating broad planning decisions into effective action, and for reviewing decisions in the light of new information. This integrated planning-execution system will be tested on the detailed "descriptive model." The detailed description may take the form of a "Monte Carlo" simulation on an electronic computer or may involve both men and machines in a "gaming laboratory." However, because such detailed simulations can be expensive and because their elaborate structure makes them inflexible, great stress will be laid on developing a system of analytic submodels which will be used to express the action of micromechanisms wherever possible. Special attention will be given to seeing how well the mathematical model controls the descriptive model under extreme operating conditions or under conditions intentionally designed to violate one or more of the simplifying assumptions upon which the model is based.

Two important advantages should result from this approach: (1) It is expected that it will furnish the originators of the mathematical model with a more or less realistic "field test" of their model and that it will stimulate them into further work to patch up its weaknesses; (2) It also is expected that the set of submodels, techniques, and procedures used to interconnect the mathematical model to the descriptive one will be ready for use as a fully integrated planning-execution system in its real world counterpart.

The second topic in the Theory of Planning and Control is:

II. Decentralized Decision-Making

Industrial planners have long speculated about the possibilities of issuing an internal currency to managers of various parts of a system to make local decisions which are optimal for the system as a whole. If these prices could easily be determined, this scheme might be an excellent way of integrating planning with execution. The practical difficulty, however, in applying this approach is that the determination of these internal prices depends upon constructing the "production function" which, according to theory, relates all the inputs of a system to its outputs.

Historically, however, economists have considered the actual construction of such a function as something outside their domain. Indeed, since this problem was more technological than economic, they deemed it a clear responsibility of the engineer. But the engineer possessed no method for translating his knowledge of machines into such economic figments as production functions, so there the matter has rested. The underlying difficulty is that the production function is really too complicated to be determined explicitly, although it can now be obtained implicitly as the by-product of a mathematical programming model.

Nonetheless, special computational methods, recently developed for solving certain large scale linear-programming models, called the decomposition principle can be viewed as an efficient decentralized decision-making process which derives its own set of internal values called "objective prices" (because the prices reflect the objectives of the system). These can be used to guide parts of the system to make a sequence of planning proposals that converge toward an optimal solution for the system as a whole. This approach might well be developed into a workable method for organizations by trials on suitable "guinea pig" problems.

Conclusion

The central theme of my paper has been Future Developments of Operations Research. I first reviewed the rapid progress in methods for handling, computation and analysis of information for operational systems. We have seen that out of this effort is emerging a new science, concerned with the problems of rapidly selecting optimal courses of action from many alternatives. This development, in conjunction with the mechanization of simple, human, control

tasks, foreshadows the automation of many higher level, mental processes. In the not-too-distant future, machines will undertake many complex control tasks.

We next discussed the role of engineering in society. We have seen that contrary to the focus of an earlier day when engineering concentrated upon the design of isolated elements and processes, recent socio-economic and technological developments have created an urgent need for analysis of complete systems and for the design of increasingly complex systems of facilities and processes.

We next saw that in the years preceding World War II, mathematics had received powerful stimulation from problems arising in pure sciences. By contrast the post-war years have seen the emergence of a mathematics rooted in the applied sciences concerned with developing mathematical procedures specifically designed to exploit the potentialities of the enormous computational power of modern day electronics. This trend will continue.

We then turned to two topics in the Theory of Planning and Execution. We first discussed the great gap that exists between planning and execution. We pointed out our belief that great economies can result from the development of integrated planning-execution models and our anticipation that they will in time provide industry with a way to make planning both effective and practical. We sketched an approach to this type of model.

Finally, we outlined an approach to decentralized decision making that could iteratively tend toward an optimal program for the system as a whole. It has the merit that the planning staff does not require detailed operating knowledge of each part and each part has a set of objective-prices to guide its day-to-day decisions. Thus we have at hand at last a theoretical foundation for a rigorous, well understood, decentralized decision-making cycle capable of development into a practical procedure in government and industry.